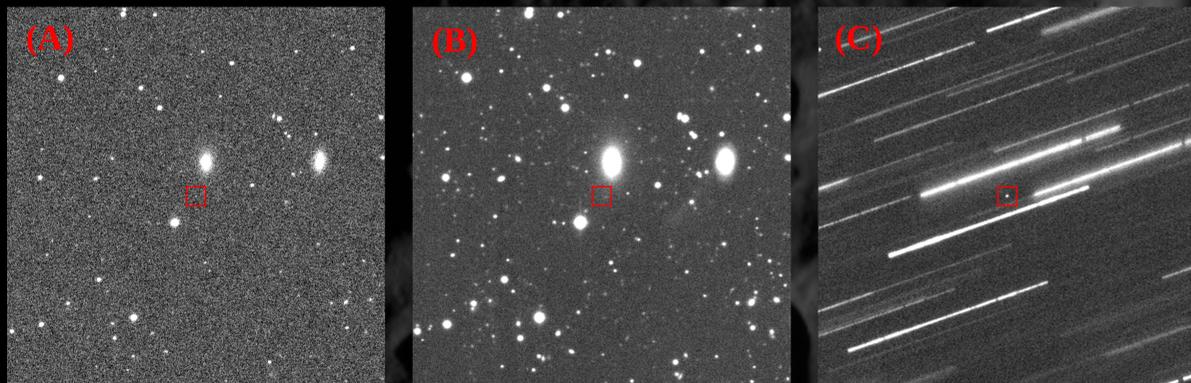


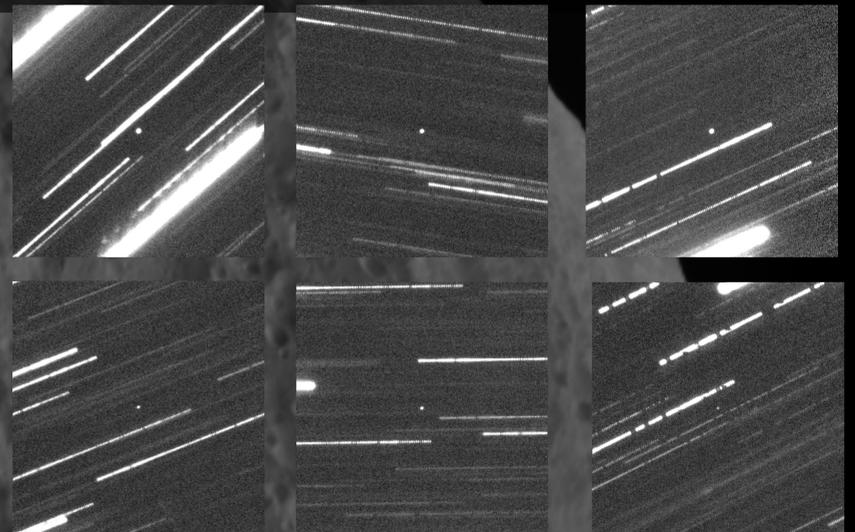
Digital Tracking Observations Discover Asteroids Ten Times Fainter than Conventional Searches

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Digital tracking is a method for asteroid searches that greatly increases the sensitivity of any telescope. While it is not original to us (e.g. Allen et al. 2001 and Bernstein et al. 2004), we are the first to develop and use it to detect large numbers of new faint asteroids from the ground. Our pilot project using the 0.9-meter WIYN telescope detected 199 asteroids ranging down to 23rd magnitude in the R band in a field of view of only one square degree. Digital tracking enables an 0.9-meter telescope to reach a flux regime previously probed only with 4-meter and larger instruments. We report promising preliminary results from a larger survey using DECam on the 4-meter Blanco Telescope at Cerro Tololo, which will reveal fainter asteroids than have ever previously been imaged. Digital tracking has the potential to revolutionize searches for faint moving objects, including Kuiper Belt objects, main belt asteroids, near-Earth objects, and even anthropogenic space debris in low Earth orbit. Our results show that there are no serious obstacles to its large-scale implementation.



The essence of digital tracking is to see faint asteroids the same way we see faint stars: by stacking many short-exposure images to obtain a long effective integration. The difficulty is that asteroids move. (A) is a single 120-second exposure centered on a main belt asteroid of R-band magnitude 21.7. The asteroid is only marginally visible, and lengthening the exposure will not increase the sensitivity – rather, it will blur the asteroid's image into a long trail that fades into the background noise. (B) is a 4.2-hour integration made by stacking 126 images like panel A. It shows much fainter stars and galaxies, but no sign of the asteroid. (C) illustrates the solution: before stacking, we offset the individual images to track the asteroid's motion. The asteroid is prominently visible, and even much fainter moving objects could be detected. The sensitivity increases approximately as the square root of the number of images stacked: more than a factor of ten for this example using 126 images. Our approach assumes that the asteroid moves in a straight line at constant angular velocity, an approximation that is sufficient for integrations up to eight hours long on main belt asteroids; one hour for Earth-crossing asteroids at 0.1 AU, and up to a week on Kuiper Belt Objects.

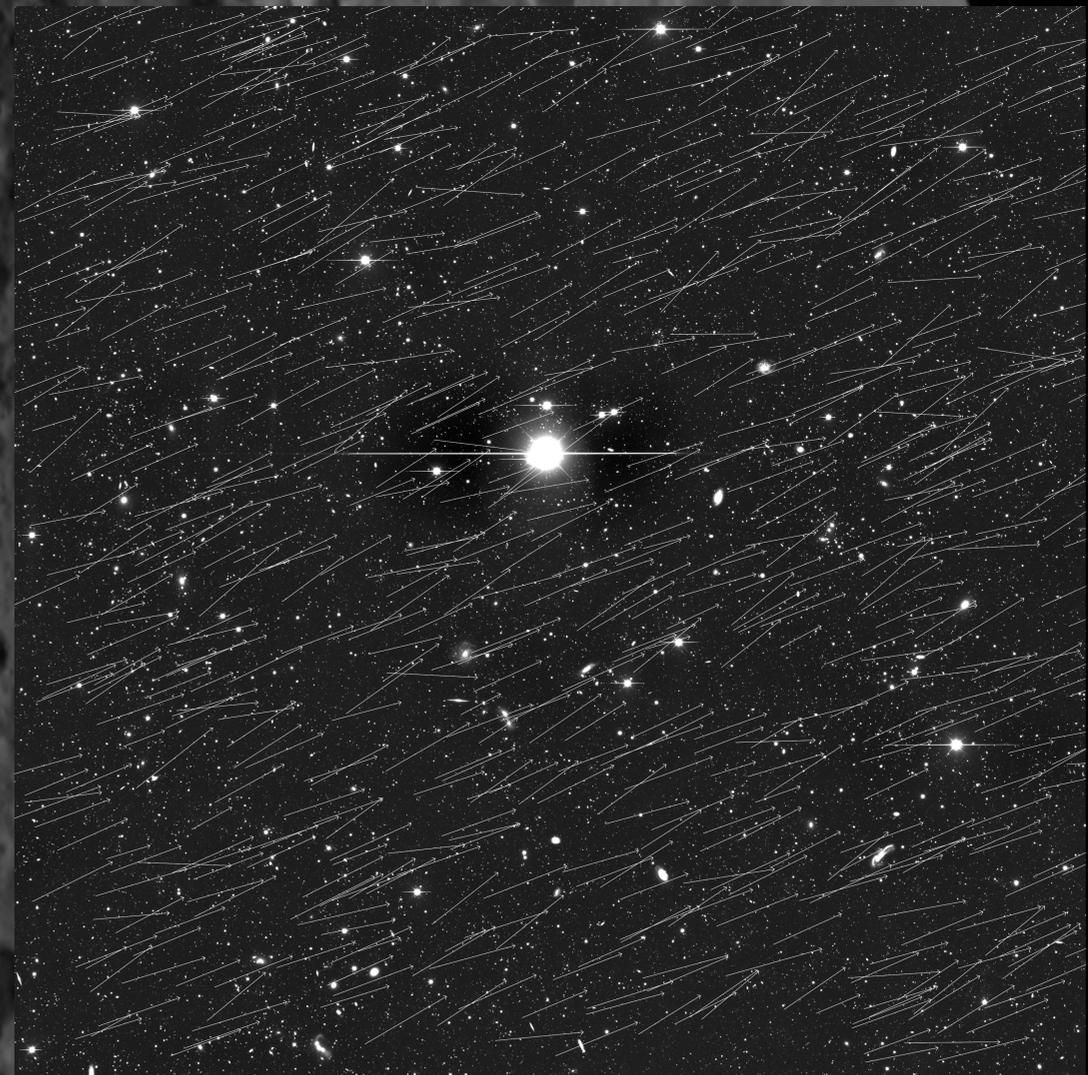


To discover new asteroids using digital tracking, we construct a separate image stack for each of several thousand trial vectors that form a finely spaced grid spanning the range of possible asteroid motions. An automated detection algorithm searches each stack for point sources above a 7-10 sigma threshold. The point sources centered in the above panels are six examples of detected asteroids*.



Right: the real on-sky tracks of asteroids detected in our digital tracking pilot project using 126 two-minute exposures with the WIYN 0.9-meter telescope at Kitt Peak. The background image against which the tracks are plotted is made from the same data, and the field of view is 1.15x1.10 degrees. Of 199 detected asteroids, 154 are new discoveries, and all are verified by consistent detection in multiple independent subsets of the images. Their magnitudes extend past 23rd in the R-band. Digital tracking enables the 0.9-meter telescope to probe a regime previously accessible only to 4-meter and larger instruments.

Left: the measured sky motions for our 657 DECcam-detected asteroids, illustrating how our digital tracking analysis covered the relevant parameter space, and how different populations of asteroids can be distinguished even at this very preliminary stage of the analysis.



Above: Preliminary results from our first major digital tracking survey, based on 116 ninety-second exposures with DECam on the 4-meter Blanco Telescope at Cerro Tololo, Chile. The field shown is one square degree and includes less than a third of the full survey area. A total of 657 asteroids are plotted above, most previously unknown and some fainter than any that have ever been imaged before.

References:

Allen, R. L., Bernstein, G. M., & Malhotra, R. 2001, ApJ, 549, L241
 Bernstein, G. M., Trilling, D. E., Allen, R. L., Brown, M. E., Holman, M., & Malhotra, R. 2004, AJ, 128, 1364

* For purposes of illustration, the stacks shown here were made from images that included background stars. Our primary digital tracking runs for automated detection of new asteroids use images that have already had the background stars subtracted.